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Evaluation of High-Performance Interference Canceller to Boost the Error Performance of The Wi-Fi 5 IEEE 802.11ac

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Abstract

The Wi-fi 5 IEEE 802.11ac can achieve throughput up to 6,933 Mbps by occupying 160MHz of bandwidth in each of eight spatial streams with 256-QAM. It provides not only very high throughput but also high wireless communications performance. However, due to the use of multiple antennas at both the transmitter and receiver sides, which operate in the same frequency band, it experiences many interference signals. Therefore, a high-performance interference canceller is highly required to cancel these interferences and get the desired information back. The conventional interference cancellers are based on linear methods, i.e., zero-forcing and minimum mean square error. Both are simple but low in performance. This paper presents the evaluation of a high-performance interference canceller based on maximum likelihood detection to boost the error performance of the wi-fi 5. Test under an in-door channel model demonstrates the superiority of this interference canceller. For a target bit error rate of 10^{-4}, it dramatically boosts the error performance by 16 dB and 17,5 dB compared to linear methods by the cost of very high complexity.

Keywords*: Wi-fi 5; IEEE802.11ac; interference canceller; MIMO; OFDM; ZF; MMSE; MLD*

1. Introduction

Wireless LAN has become the most widely used wireless networking technology to communicate data, images, voice, and even video streaming. During its development, wireless technologies have always faced classical channel problems, i.e., multipath fading. Moreover, as the number of users dramatically increases, the techniques to improve channel efficiency become crucial.

A combination of Orthogonal Frequency Division Multiplexing (OFDM) and Multi Input Multi Output (MIMO) is a key to answering the above problems. OFDM is a multicarrier transmission technique in which each subcarrier is orthogonal to the others. It divides high-rate data streams into several low-rate data streams and modulates each with an orthogonal subcarrier. This technique makes multipath frequency selective fading channel treated as a flat fading channel, which is easier to compensate. On the other hand, MIMO employs several antennas on both the transmitter and receiver sides, forming several parallel independent channels as spatial streams. This technique would broaden channel capacity without additional bandwidth.

OFDM is implemented in Wi-Fi2 IEEE 802.11a to gain throughput up to 54 Mbps in SISO (Single-Input Single-Output) system. It operates in a 5 GHz frequency band. Due to the demand for very high throughput communications, IEEE continues to extend this Wi-Fi 2 to Wi-Fi 5 IEEE 802.11ac with MIMO and wider bandwidth so that it can achieve a maximum throughput of 6,933 Mbps with eight spatial streams in 160MHz bandwidth. It is also backward compatible with the previous Wi-Fi IEEE 802.11a/b/g/n. (“IEEE Standards Association, IEEE 802.11ac” 2013.).

By setting the modulation coding scheme (MCS) to 9, the Wi-Fi 5 IEEE802.11ac can give a throughput of 3,466 Mbps. A comparison between linear and non-linear techniques to cancel the interferences under indoor channel model B was presented by (Syafei et al., 2019).

The Wi-Fi 5 becomes an emerging WLAN at 5 GHz. It accomplishes a very high data rate based on three distinct measurements: wider bandwidth, denser modulation, and higher resolution for narrow and medium bandwidth channels. Some techniques to improve the performance of this Wi-Fi 5 was presented by (Yonis, 2019).

Although the sphere decoder (SD) is a powerful detector for MIMO systems, it has become

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computationally prohibitive in a situation where a large number of antennas are employed. To overcome this challenge, the authors proposed fast deep learning (DL) aided SD (FDL-SD) and fast DL-aided K-best SD (KSD, FDLKSD) algorithms. Compared to existing DL-aided SD schemes, the proposed schemes are more advantageous in both offline training and online application phases. (Nguyen et al., 2021).

SD enables real-time quasi-optimal symbol detection for MIMO communication systems via custom circuit accelerators. Configurable SDs allow accelerator costs to be balanced with detection accuracy for the most constrained MIMO environments, such as power-constrained Internet-of-Things (IoT) scenarios. However, this high detection accuracy comes at high accelerator cost. A paper proposed a Robust Bounded Spanning with Fast Enumeration (R-BSFE) approach for channel matrix pre-processing and symbol enumeration to maintain quasi-ML accuracy whilst reducing complexity by up to 74%. This enables accelerators for 802.11n on Xilinx FPGA with significantly lower cost and higher throughput. To the best of the authors’ knowledge, the accelerators produced are the highest performance, lowest cost quasi-ML SD accelerators on record. (Wu and McAllister, 2021).

A signal detection using deep learning techniques in a MIMO decode-forward relay channel is considered (Jin & Kim, 2019). Some suboptimal detectors exist in the channel, such as the near maximum likelihood detector and the NML with two-level pair-wise error probability detector. However, the NML detectors require an exponentially increasing complexity as the number of transmit antennas increases. More seriously, without the channel state information of the source-relay link, there is no detector that can achieve good performance even at high complexity. The complexity analysis and simulation results validate the superiority of the proposed DL-NML detector.

Simulation results are presented for the nonline of sight 3D-UMa model of 5G QuaDRiGa 2.0 channel for 16 highly correlated single-antenna users with QAM16 modulation in 64 antennas of Massive MIMO system. The performance was compared with MMSE and other detection approaches. (Ivanov et al., 2020).

An implementation of Wi-Fi5 for a residential scenario was simulated using NS-3. Different MCS, frame aggregation, antenna numbers, throughput, delay, jitter, optimum range for good put, and effect of station density per access point in a network had been observed (Amewuda et al., 2018).

A joint scheme antenna and relay selection can be used to broaden the wireless communication capacity. Analyzing the DL-MIMO-DF relay network by considering Nakagami fading as a model of channel gains showed the superiority of the proposed JS. (Zhang and Ge, 2017).

A design and VLSI architecture of Multi Sphere was proposed by (Nikitopoulos et al., 2018). It was claimed that for a 10 × 10 MIMO spatially multiplexed system with 16-QAM modulation and 32 processing elements, the MultiSphere architecture could reduce latency by 29× against well-known sequential SDs and achieve up to approximately 9× increased energy efficiency.

Two methods have been proposed for the Wi-Fi 5 AP, i.e., dynamic channel assignment using TurboCA and fast ACK. The evaluation showed that these methods were able to increase network capacity and performance based on users' experience. (Bhartia et al., 2017).

A low-complexity MIMO decoder called one-bit-SD for an uplink massive MIMO system with one-bit ADC has been proposed. To lower the complexity, it divided the received signal vector into multiple reduced dimension sub-vectors and then generated multiple spheres in parallel. The simulation showed that it could attain near-optimum performance with low complexity (Jeon et al., 2018).

An efficient high-level parallel SD scheme based on the master paradigm was proposed. It allows multiple SD instances to simultaneously explore the search space while mitigating the overheads from load imbalance. Further, a combination of SD and K-best provided accurate detection of SD with reduced complexity by K-best. It is claimed that it could increase the speed by 5x and allow the use of up to 100 antennas (Dabah et al., 2020).

SD was implemented on Virtex-7 FPGA, and 28 nm ASIC technology was observed. The initial radius was adjusted carefully to lower the complexity, and optimization at tree searching reduced the number of visited nodes. This combination decreased the latency, and the SD was able to be downloaded onto the target LSI with Eb/N0 more than 4 dB. (Vordonis and Paliouras, 2019).

Transmitting several independent data in the same channel at the same time is called spatial multiplexing in the MIMO system. On the receiver side, a special decoding technique is needed to recover the desired transmitted information. This MIMO decoder is also named interference canceller since it cancels the other unwanted signals that come along together. Conventional Wi-Fi 5 IEEE 802.11ac cancels the interferences based on one of the two linear methods, i.e., Zero Forcing (ZF)

Table 1. Development of the Wi-Fi 2 to Wi-Fi 5.

IEEE 802.11	**a**	**b**	**g**	**n**	**ac**
Generic Name	WI-Fi2	WI-Fi2	WI-Fi3	WI-Fi4	WI-Fi5
BW (MHz)	20	20	20	40	160
FFT Size	64	-	64	128	512
NSS	1	1	1	4	8
Modulation (QAM)	64	64	64	64	256
Coding rate	3/4	3/4	3/4	¾	5/6
Operating Frequency GHz)	5	2.4	2.4	2.4 & 5	2.4 & 5
Throughput (Mbps)	54	11	54	600	6933

and Minimum Mean Square Error (MMSE). Both of them are simple but low in performance. A well-known technique that has optimum performance in soft-decision detectors is the Maximum Likelihood Detection (MLD). It is optimum since it calculates the shortest distance between the received symbol and all possible symbol candidates.

This paper presents an evaluation of high-performance interference cancellers to boost the error performance of the Wi-Fi 5 IEEE802.11ac. A test of 4x4 MIMO configurations with 64 QAM is conducted under the in-door channel model.

2. Materials and Method

2.1 Material of the Wi-Fi 5 IEEE 802.11ac

As an extension of the existing Wi-Fi IEEE802.11a/b/g/n with more spatial streams and wider bandwidth, the Wi-Fi 5 IEEE 802.11ac promises more robust and much higher throughput. Within the same 40 MHz of bandwidth, the Wi-Fi 5 offers six folds in throughput, and by expanding the bandwidth to 160 MHz, it rises twelve times of throughput compared to The Wi-Fi 4 IEEE 802.11n. Therefore, the Wi-Fi 5 IEEE 802.11ac is called very high throughput (VHT-WLAN). Table 1 lists the development of WLAN systems from Wi-Fi 2 to Wi-Fi 5.

2.1.1 MIMO in Wi-Fi 5 IEEE 802.11ac

Nomenclature: A bold printed character represents a matrix. $(\bullet)^H$is a Hermitian matrix or transpose conjugate. $(\bullet)^{-1}$ is inverse matrix. **I** is the identity matrix.$\|\bullet\|$ represents Euclidean norm.

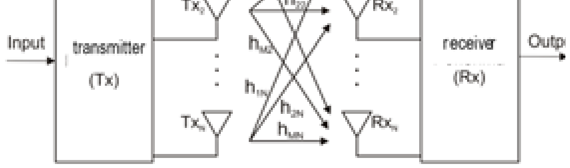

Figure 1. *N* x *M* MIMO system

MIMO is a kind of diversity technique, i.e., spatial diversity, that reduces fading and interferences from other users. It also increases the data rate without sacrificing the bandwidth. MIMO configuration with *N* transmit antennas and *M* receive antennas is shown in Fig. 1.

Channel impulse response (CIR), h_{MN} represents the propagation channel from *the M*-th receive antenna to *the N*-th transmit antenna. At the receiver antennas, the received signals can be written as Eq. (1).

$$\mathbf{y} = \mathbf{Hs} + \mathbf{n} \tag{1}$$

where **H** is a matrix of CIR, **s** is the transmitted symbols, and **n** is the additive white Gaussian noise.

2.1.2 Interference Canceller

Each antenna receives all the transmitted symbols. At the first receive antenna, the received signal would be calculated using Eq. (2).

$$y_1 = \sum_{i=1}^{N} h_{1i} s_i \tag{2}$$

From the general expression of the received signal in Eq. (1) it can easily be derived from Eq. (3).

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & \cdots h_{1N} \\ h_{21} & h_{22} & \cdots h_{2N} \\ \vdots & \vdots & \ddots \ \vdots \ \hat{\mathbf{s}} \\ h_{M1} & h_{M2} & \cdots h_{MN} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_N \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix} \tag{3}$$

Since all symbols are mixed in each received signal at each receive antenna, the MIMO decoder or the interference canceller is needed to obtain the information by decoding or canceling the interferences. Conventional WLAN 802.11ac cancels the interferences based on linear methods, such as ZF and MMSE, which are discussed briefly as follows:

2.1.2.1 *Zero Forcing (ZF)*

ZF method eliminates the channel's effect by simply multiplying the received signal by the inverse of the estimated channel matrix without considering the additive noise. The desired information is obtained by Eq. 4.

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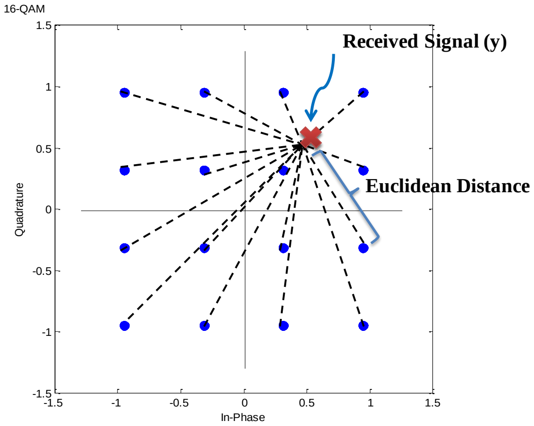

Figure 2. Illustration: When a signal (y) is received, the MLD calculates the Euclidean distance to all symbol candidates and finds the min.

(4)

where the weight of **W** is set so that **WH** = **I**, which would be satisfied by.

$$\mathbf{W} = (\mathbf{H}^{\mathbf{H}}\mathbf{H})^{-1}\mathbf{H}^{\mathbf{H}} \tag{5}$$

Eq. 4 and 5 produce an estimated symbol $\hat{\mathbf{s}}$ which contains unwanted noise parts, as.

$$\begin{gathered}\hat{\mathbf{s}} = \mathbf{W}\mathbf{y} \Leftrightarrow \hat{\mathbf{s}} = \mathbf{W}(\mathbf{H}\mathbf{s} + \mathbf{n}) \\ \Leftrightarrow \hat{\mathbf{s}} = \mathbf{W}\mathbf{H}\mathbf{s} + \mathbf{W}\mathbf{n} \Leftrightarrow \hat{\mathbf{s}} = \mathbf{s} + \mathbf{W}\mathbf{n}\end{gathered} \tag{6}$$

2.1.2.2 *Minimum Mean Square Error (MMSE)*

Differs from ZF, the MMSE method considers reducing the additive noise when defining the coefficient weight **W** as

$$\mathbf{W} = (\mathbf{H}^{\mathbf{H}}\mathbf{H} + \mathbf{nI})^{-1}\mathbf{H}^{\mathbf{H}} \tag{7}$$

Here, we can see that in the absence of noise (**nI** = 0**)**, Eq. 7 will return to Eq. 5.

2.2 Method to improve error performance of the Wi-Fi 5 IEEE 802.11ac

Rather than using linear methods to cancel the interferences, a non-linear method known as maximum likelihood detection (MLD) is evaluated. MLD compares the Euclidean distance of the received signal to all possible transmittable symbols or symbol candidates to find the closest one, i.e., the most likely symbol as represented in Eq. 8.

$$\hat{s}_{ML} = argmin\|\boldsymbol{y} - \mathbf{H}\hat{\boldsymbol{s}}\|^2 \tag{8}$$

where $\hat{\mathbf{s}}_{\mathbf{ML}}$ is the estimated symbol, **y** is the received signal, **H** is the channel impulse response from *M* receive antennas to *N* transmit antennas and $\hat{\mathbf{s}}$ is the symbol candidate.

So $\hat{\mathbf{s}}_{\mathbf{ML}}$ is obtained by finding the Euclidean distance between the received signal from the transmitter and the multiplication of channels with candidates' symbol of the transmitted signal. The MLD selects the $\hat{\mathbf{s}}$ that produces the smallest distance, as illustrated in Figure 2.

Figure 2 shows the MLD in the case of the 16QAM constellation. The Y-axis shows the quadrature (imaginary), and the X-axis shows the in-phase (real). When the received signal vector in the receiver ($\boldsymbol{y}$) falls at any point in the constellation map, the MLD calculates its Euclidean distance to all 16 symbol candidates and finds the minimum one. The smaller distance of the received signal with the symbol means the greater likelihood of them.

Since the MLD calculates every possible distance to all candidate symbols, it employs many computations. The complexity is determined by the type of modulation and the number of transmit antennas, as Eq. 9.

$$K = M^{N_t} \tag{9}$$

where M is the number of constellation points, and N_t is the number of transmit antennas.

For BPSK modulation with four transmit antennas, the MLD calculates a minimum distance of 2^4 = 16 combinations. For 64QAM modulation with the same parameters, the MLD needs to find the smallest value of 64^4 = 16.777.216

Calculation of the estimated symbol when using BPSK modulation with four transmit and receive antennas can be expressed as Eq. 10.

$$\hat{s}_{ML} = \left\| \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} - \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} \hat{s}_1 \\ \hat{s}_2 \\ \hat{s}_3 \\ \hat{s}_4 \end{bmatrix} \right\|^2 \tag{10}$$

where the value of $\hat{s}_1, \hat{s}_2, \hat{s}_3, \hat{s}_4$ is +1 or -1. MLD solution shall choose the minimal value of all 16 combinations of $\hat{s}_1, \hat{s}_2, \hat{s}_3, \hat{s}_4$, such as Eq. 11.

$$\hat{s}_{ML1} = \left\| \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} - \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} +1 \\ +1 \\ +1 \\ +1 \end{bmatrix} \right\|^2$$

$$\hat{s}_{ML2} = \left\| \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} - \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} +1 \\ +1 \\ +1 \\ -1 \end{bmatrix} \right\|^2$$

$$\hat{s}_{ML3} = \left\| \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} - \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} +1 \\ +1 \\ -1 \\ +1 \end{bmatrix} \right\|^2$$

$$\vdots$$

$$\hat{s}_{ML16} = \left\| \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} - \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix} \begin{bmatrix} -1 \\ -1 \\ -1 \\ -1 \end{bmatrix} \right\|^2 \tag{11}$$

Estimation of the transmitted symbol is selected based on the minimum value of the sixteen values above:

- If the minimum value is $\hat{s}_{ML1}$ the symbol is [1,1,1,1],
- If the minimum value is $\hat{s}_{ML2}$ the symbol is [1,1,1,0],
- If the minimum value is $\hat{s}_{ML3}$ the symbol is [1,1,0,1],

$$\vdots$$

- If the minimum value is $\hat{s}_{ML16}$, the symbol is [0, 0, 0, 0]

3. Result and Discussion

The simulation parameter is listed in Table 2. The term MCS is an abbreviation of the Modulation Coding Scheme. This is a simple representation of the setting of the Wi-Fi 5 IEEE 802.11ac. It determines the modulation type, coding rate, number of spatial streams, and hence the throughput. Here, the MCS is set to be MCS 8 and MCS 9 to examine the Wi-Fi 5 IEEEE 802.11ac to provide its highest throughput. The setting of MCS 8 means that the Wi-Fi 5 IEEE 802.11ac uses 256 QAM modulation with 3/4 coding rate. When MCS 8 is set to eight spatial streams with 160 MHz of bandwidth for each stream, the Wi-Fi 5 IEEE 802.11ac can provide a throughput of up to 6,240 Mbps. The difference between MCS 8 and MCS 9 is in the coding rate. MCS 9 uses a 5/6 coding rate so that it can provide higher throughput, e.g., 6,933 Mbps.

Table 3. Complexity comparison of interference cancellers based on ZF, MMSE, and MLD with different modulation and number of transmit antennas.

Number of Tx antenna	Modulation	Complexity		
		ZF	MMSE	MLD
1	64 QAM	2	2	2^{6}
2	64 QAM	6	6	2^{12}
3	64 QAM	12	12	2^{18}
4	64 QAM	20	20	2^{24}
5	256 QAM	30	30	2^{40}
6	256 QAM	42	42	2^{48}
7	256 QAM	56	56	2^{56}
8	256 QAM	72	72	2^{64}

Performance comparison of the three interference cancellers in the Wi-Fi 5 IEEE802.1ac under the in-door channel model for the MCS 8 and MCS 9 settings are shown in Figure 4 and Figure 5, respectively.

For MCS 8, which is shown in Figure 4, to achieve BER 10^{-4}, the interference canceller based on ZF and MMSE need SNR 46 dB and 44 dB, respectively, while the interference canceller based on MLD needs only 31 dB of SNR. This value shows that the error performance of the Wi-Fi 5 IEEE 802.11ac is boosted to 15 dB and 13 dB.

When the Wi-Fi 5 IEEE 802.11ac is set to MCS 9, to achieve BER 10^{-4}, the interference canceller based on ZF

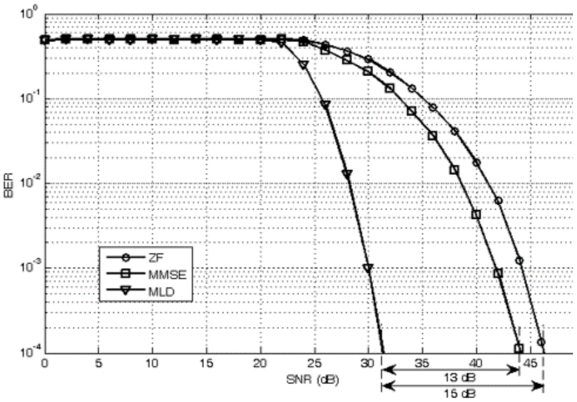

Figure 4. Performance comparison of interference canceller based on ZF, MMSE, and MLD for MCS 8

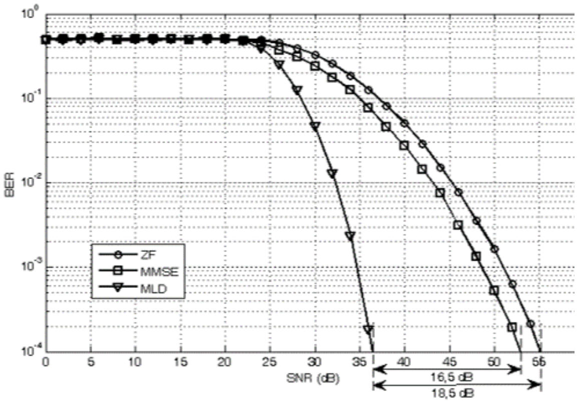

Figure 5. Performance comparison of interference canceller based on ZF, MMSE, and MLD for MCS 9 of Wi-Fi 5 IEEE 802.ac.

and MMSE needs SNR 55 dB and 53 dB, respectively, while the interference canceller based on MLD needs only 36,5 dB of SNR. This result shows that the error performance of the Wi-Fi 5 IEEE 802.11ac is dramatically boosted to 18,5 dB and 16,5 dB, as shown in Fig. 5.

On the other side, the complexity of those interference cancellers should also be taken into consideration. The linear methods, e.g., ZF and MMSE, have almost the same low complexity, which is determined by the number of transmit antennas regardless of the modulation type, as expressed in Eq. 12.

$$K = N_t^2 + N_t \tag{12}$$

Where N_t is the number of transmit antenna. The complexity of MLD is expressed in Eq. 9 above. A comparison of the complexity of three interference cancellers is listed in Table 3.

Here, it can be verified that the interference canceller, which is based on the MLD method, is very complex. This computation needs a lot of logical gates that lead to a very big circuit. The implementation of this high-performance interference canceller will become a problem if the complexity is not reduced in advance.

4. Conclusion

We have evaluated a high-performance interference canceller based on the maximum likelihood detection (MLD) method and compared it to the conventional ones, which are based on linear methods, i.e., zero-forcing (ZF) and minimum mean square error (MMSE). A comparison is made in the Wi-Fi 5 IEEE 802.11ac environment, which is set to MCS 8 and 9 to provide the highest throughput of 6,240 Mbps and 6,933 Mbps, respectively, under the in-door channel model. For target BER 10^{-4} in MCS 9, the MLD dramatically improves the error performance of the Wi-Fi 5 IEEE 802.11ac with 16,5 dB and 18,5 dB compared to MMSE and ZF, by the cost of very high complexity. Our subsequent work shall search for high-performance but low-complexity interference cancellers for the next-generation Wi-Fi 5/6/7 IEEE 802.11ac/ax/be.

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